Journal of Building Engineering 20 (2018) 235–247

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment

Ali Tighnavard Balasbaneh[a,*], Abdul Kadir Bin Marsono[b], Seyed Jalal Khaleghi[c]

[a] Construction Management, Faculty of Civil Engineering, University Technology Malaysia, Malaysia
[b] Structure and Materials Department, Faculty of Civil Engineering, University Technology Malaysia, Malaysia
[c] Construction Management, Deylaman Institute of Higher Education, Iran

ARTICLE INFO

Keywords:
Hybrid timber structure
Sustainable design
Life cycle cost
Life cycle sustainability assessment
Social life cycle assessment
Climate change mitigation

ABSTRACT

The impact of different hybrid timber building construction on three different categories namely: environment, economic and social is analyzed in this research. Five types of hybrid timber structure have been chosen in this study toward finding the most optimum choice for Malaysian low income housing. The base material of all case studies are wood and only main frame of structures are different. The environmental impact of each individual design encompasses material extraction, transportation, construction, maintenance and end-of-life phases. The life cycle aspect of current research is evaluated for global warming potential (GWP), human-toxicity potential (HTP), eutrophication (EP), fossil depletion (FDP), acidification (AP), life cycle cost (LCC) and social life cycle assessment (SLCA). The result revealed the different emissions between various structural schemes in all stages. Decision making process was oriented to sustainability as the hybrid steel stud & timber (T2) generally performed better than timber structure with concrete, LVL or GLT with steel. Particularly, T2 had the lowest GWP (3.31E + 3 kg-CO_2-eq) and LCC (212,750 MYR) which was the lowest in comparison with other hybrid timber structures. Also the result of job creation revealed that timber sector will provide higher wage not only for existing employees but for timber sector regarding creating higher job possibility. The sensitivity analysis was accomplished on electricity usage and assumed instead of full fossil fuel mix electricity applied for acquiring construction material on mill. The result shows almost 15–30% less GWP emission for all building structure.

1. Introduction

The bio-economy strategies aim to change current fossil-fuel based production activities into production processes based on biological renewable resources [63]. Therefore, wood-based products will play a pivotal role for this transition. To comply with such transition procedures, the potential environmental, economic and societal implications have to be assessed and monitored for any path or production. Sustainability has obviously emphasized that assessing process or product must be on three aspects including environmental, economic and social. However, almost all existing studies in literature focus only one or at most two above perspectives, but to our knowledge, no study has combined the three criteria. Design of building is normally begun by making a number of important decisions including selection of the structural system.

Finding life cycle optimized building structure designs could be really challenging task for environment engineering and has become a main topic of international debate. The '2030 climate and energy framework' by EU Commission declared a fundamental target for 2030 with at least 40% cut in GHG emissions, 27% share from renewable energy and the last 27% improvement in energy efficiency (European Commision [1]). The construction industry is one of the influential industries in most nations responsible for a high quantity of materials consumption and impact on climate change. Buildings contribute up to 30% of global annual greenhouse gas (GHG) emissions and consumes up to 40% of all energy [47]. Therefore, documenting and controlling load from the building sector is one key to achieving sustainable development. Malaysia is one of the countries where the amount of GHG

Abbreviations: GWP, Global Warming Potential; AP, Acidification Potential; EP, Eutrophication Potential; FDP, Fossil Depletion Potential; HTP, Human-toxicity Potential; LCC, Life Cycle Cost; SLCA, social life cycle assessment; MYLCID, Malaysia Life Cycle Inventory Database; GLT, Glued Laminated Timber; LVL, Laminated Veneer Lumber; HIS, Household income Survey; PLI, Poverty Line Income

* Corresponding author.
E-mail addresses: alitighnavard@gmail.com (A.T. Balasbaneh), akadir@utm.my (A.K.B. Marsono), sj.khaleghi@gmail.com (S.J. Khaleghi).

https://doi.org/10.1016/j.jobe.2018.07.006
Received 7 February 2018; Received in revised form 6 July 2018; Accepted 6 July 2018
Available online 10 July 2018
2352-7102/ © 2018 Elsevier Ltd. All rights reserved.

emission (change in $CO_{2)}$ suddenly increased by 345% from 1990 to 2015 [2]. However, almost 40% of the world's energy consumption and one third of related GHG emissions are attributable to the building sector as it creates significant economic, environmental and social impacts UNEP (2008), USGBC [51] and IEA [52] and this trend may seem to be rising since the report was released. Hereby, Malaysia also aims to reduce its GHG emissions intensity by 45% by the year 2030 [3]. The last few years has witnessed significant development toward design sustainability practice for building sector, both by public and private sector [4].

Based on Housing and Population Census Malaysia [10], population in Malaysia has been growing for the past 40 years ago and most of this new population immigrate from rural to the capital cities. Therefore, the need to build new construction immediately increased. In the past 40 years, wood materials on building scheme, especially as structure, have dropped significantly in Malaysia due to its short life short span. In contrast, Wood not only decreases CO_2 emission but is also moving toward Non Renewable compared to concrete or steel, etc. For developing countries such as Malaysia, the building sector usually represents up to 40% of Gross Domestic Product (GDP). Construction data was reported at 16,765.00 MYR in Sep 2017, and only 6468.00 MYR in Mar 2010 [48,58]. These numbers highlight the importance of reducing the usage of scarce resources and avoiding the harmful emissions from the construction sector, for the sake of both environmental and social well-being. Therefore, use of renewable material in building construction is the solution. Normally decisions regarding the choice of one type of building scheme over another are based on not only economic considerations, environmental issues but job creation, which also has a vital role for achieving sustainable development.

Based on review study by Sartori and Hestnes [12] of 60 different buildings, carbon emission of building materials accounts for up to 46% of total life cycle emissions for low-energy buildings and up to 38% for conventional buildings. An increase of 42–68% of carbon emission from building suggests that building sector needs to think about the reduction possibilities of its related carbon emissions [13], while most of these emissions from construction are contributed to the residential building sector [27]. Pérez-Lombard et al. [53] stated that GHG emissions from buildings sector continue to rise at an annual rate of 1.5%. For example, some countries such as UK, building sector contributed approximately 50% of total emission [54]. Goverse et al. [19] claimed that technically 50% reduction in CO_2 emissions could be achieved by utilizing wood instead of concrete as building structures.

Himpe et al. [14] suggested that Wood panels were decisive factors in the life cycle embodied energy of building services. However, almost no research has been accomplished on SLCA of building material in construction and specifically on timber. In another study, Hossaini et al. [24] accomplished both LCA and LCC of concrete and wood mid-rise building constructions in Canada and their result indicated that wood building has a lower LCC compared to concrete. Islam et al. [21] also accomplished both LCA and LCC analysis of alternative wall in Australia. Sathre [85] assessed the cost of wood and non-wood building and result revealed that wood has a lower cost which mainly related to the lower energy cost of material in their material manufacture phase. Kim et al. [23] evaluated the two conventional types of structural frame between those consisting of concrete and those consisting of steel frame on the construction stage for both LCC and LCA evaluation. In comparison of total cost between wooden, concrete and steel applications, wood has been commonly seen as a cost-effective option [83]. The other study on composite structure [20], accomplished acoustic performance of timber-concrete floor. Timber composite structure is not limited to wall or floor but even can be used in bridge structure [89].

In summary, all research paper in literature so far indicate that timber is an alternative to concrete and steel because it is considered as a material which can compete, first environmentally due to having less GHG emissions, while there has been no specific distinguished research accomplished about different timber building structure toward sustainability. To our knowledge, there are no references combining environmental, social and economic in an integrative, triple-bottom line analysis of dedicated construction material systems. This paper intended to fill the gap on current knowledge by evaluating the environmental, economic impacts and social impact of using wood-base structure along alternative material in frame such as precast concrete, engineered wood, steel stud, steel sandwich plate structural products in Malaysian residential building constructions. The outcome of this research can be used in design stage for residential building designers and government policy maker in residential sector to make choice on the environmental, economic and social impacts of the selected construction materials, which can make huge differences for moving toward timber industry. The research was aimed to assess the LCA, LCC and SLCA of different timber composite structure from timber house. It is very important to understand the environmental suitability and sustainability of these composite structures.

2. Methodology

For accomplishing the Life Cycle Sustainability Assessment (LCSA) [65] combing the result of life cycle applications (LCA, LCC, and S-LCA) should first be considered. Life cycle assessment (LCA) basically has been developed less than two decades ago and it accomplished the environmental impact of product or process over its life span.

However, in recent years' LCC research had been evaluated by researcher alongside of LCA to obtain clear vision of product. But working on assessment of the social impact of product over its life cycle is completely new and began only a few last ago. Table 1 shows the sustainability framework of hybrid timber assessment that evaluate not only LCA, LCC but SLCA of timber as well.

2.1. Life cycle assessment and databases

LCA generally is a method to comprehend the environmental impacts between two or more processes or products which are used to compare wood-based construction building in current study. The software used for analyzing the environmental impact is SimaPro v.8.0.4.30 modelling. This software has already been designed under the ISO14040 [22] regulation. LCA covers all stages of material including production, use and disposal. It is also considered as a cradle of grave product which encompasses all activity and energy use during the life span of building.

LCA study happened to evaluate the processes of energy flow of a system and is generally quantified upstream started from extraction of raw material, transportation, construction, maintenance until downstream, which included the disposal flows of a product. Subsequently, environmental impact either, global and regional, of energy consumption and waste generation were calculated. Based on ISO 14040 which regulated any LC study, it should consist of four steps and include goal and scope definition, life cycle inventory (LCI) and life cycle impact assessment (LCIA), which related to the choosing method and finally interpretation or result.

Table 1
Framework of sustainability assessment of current research.

Sustainability Of Building		
Environment impact	Economy impact	Sociology impact
Global Warming Potential (GWP)	Life cycle cost	Wage of foreman
Fossil Depletion Potential (FDP)	Present Value	Number based on Job creation
Acidification Potential (AP)		
Eutrophication Potential (EP)		
Human-toxicity Potential (HTP)		

The loop for renovation in this research is adopted from average period time in the literature. In this research the renovation was only made after 25 years. The renovation only related to the external timber wall (i.e. plasterboard, plaster render) that were replaced during the minor renovation and data is based on national association of home builders (NAHB) and material producers [78]. The other maintenance activities include painting of walls and varnishing of wood surfaces every 10 years based on the report by NAHB, as suggested by Iyer-Raniga and Wong [79], four times over a 50 years' lifetime. Concrete and steel have longer durability, so no replacement was considered.

2.1.1. Life-cycle inventory and life cycle impact assessment method

The embodied energy has been measured from cradle to grave and it contributed to the energy for all process of material circle such as extraction, fabrication, transportation, etc. Embodied carbon calculations therefore require an understanding of all of the materials, or ingredients, within your products, and all activities related to those materials, such as processing and transport. Heating & lighting of a building are not considered embodied carbon, they are instead a carbon footprint.

Functional unit of this research was performed as whole structure scheme of single story residential building over 50 years of its life span. The system boundaries of research provide the cradle to grave LCA of hybrid timber structure, which depending on case study, would be concrete and timber combination for building scheme or steel covering timber saw in post & beam, while the walls are considered as timber prefabricate wall or LVL with steel or GLT combined with steel used as post & beam. The system boundary was set as cradle to grave and encompasses material extraction, manufacturing, construction, maintenance and disposal. End of life scenario, depending on the kind of materials, could lead to landfill, recycle or reuse. Furthermore, following previous research [25] operation phase has not been considered in the assessment since it does not affect the structural of building. Therefore, it will be assumed that various building structures have no effect on operational application during the life span.

In the current study, since base material for all case study is timber, the system boundary distinguished such as plantation and continue with harvesting, second thinning or final harvesting depending on the products. For structure containing engineering wood, logs were then transported to the mill to produce LVL and GLT combined with steel stud. The structural products were transported to the building construction site using road lorry. For the end-of-life stage, both LVL and GLT have been assumed as incineration for energy recovery. The scenario for timber wall material is considered as incineration which leads to energy recovery following previous study [33] and final decision for steel is considered the end of life if recycling 100% of material. Also, in first case study where the structure contains precast concrete, the decision for end of life is to send material to landfill. The life span of building was estimated as 50 years which is based on Malaysia's average building service life [35].

This study was based on series of assumptions. For instance, all the machinery used for cutting the wood and installing the components are using electricity from Malaysian mix local electricity data [38, 44, 84]. The description of LCI [80] is calculating the energy use of any process including the beginning from raw material and all input and output that existed in the system boundary. For LCI, the Malaysia Life Cycle Inventory Database (MYLCID) [77] has been used for raw material such as timber, concrete and steel production, as well as diesel for transportation, due to produce significant result for Malaysia. MYLCID data was also applied for Electricity usage in sawmill diesel fuel and lubricants used to power equipment for a series of forestry machinery, which is allocated as 96.63% source of electricity production in 2014 in Malaysia. In this study, to localize the final result, Ecoinvent database has been adopted to Malaysia by replacing the electricity data set as suggested by previous research due to data limitation. Electricity used during greenhouse operations, diesel fuel and lubricants used to power equipment for a series of forestry machinery are also accounted.

Life cycle impact assessment (LCIA) methods in this study is a multi-category and it is defined as ReCiPe Midpoint (H) following previous study [74]. ReCiPe Midpoint (H) method [40,71] was used for the characterization of emissions into the relevant impact categories except for the AP category for which the CML 2001 [72] method was used [73]. The GWPIPCC is a method for assessing building organizations and recommendations have developed to diminish environmental impacts of the building industry. Some other aspects that were evaluated are Fossil Depletion Potential (FDP) Acidification Potential (AP), Eutrophication Potential (EP), and Human-Toxicity Potential (HTP).

2.2. Economic assessment, Life Cycle Cost (LCC)

The LCC assessment was accomplished following the Department of Statistics Malaysia Official Portal and Malaysia Official Portal (CIDB [32]), which considers every relevant cost stage over the full life span of materials. The entire cost has been converted to the 2016 Malaysian ringgit Present Value (PV). Thus, the LCCs of each building structure was calculated by an Excel spreadsheet model toward estimation for period of 50 years and the prices used in this study were based on average market prices in Malaysia. Choosing a project exclusively based on economic considerations could be premature, because it may forgo the opportunity to maximize sustainability of the national social housing program. The LCC of wood material encompasses all raw material extraction (logs), or steel (stud) and concrete (post & beam) production, manufacturing, transportation, construction process, maintenance of external wall and painting, demolition (reuse or landfill). The carbon offset form wood incineration in the final disposal stage and recycling for end of life of steel is also included.(Table 2)

First, based on Akasah and Rum [31] and Buys et al. [30] research result, the majority of construction projects in Malaysia have not implemented LCC in the management strategies. This is mostly attributed to their reluctance to commit to a change in their management policy. Therefore, there is obvious evidence as to which construction material will eventually have the lowest cost in Malaysian market. To introduce the nest method of construction there should be a strong correlation between construction sector and economic growth of Malaysia [15]. The assumptions of this research, respectively, are inflation rate 3.4% [81], discount rate 4.5%, electricity cost 38.53 Sen in Peninsular Malaysia (however in Sabah and Labuan at 33.32 Sen per kWh) and finally transport cost 0.31 MYR.

2.3. Social life cycle assessment

The United Nations Environment Programme (UNEP)-SETAC [66,67] declared that inventory data for social assessment can be interpreted and evaluated while, there is not certain method has been introduced for social impact yet. Although the argument has been made since 1990s about the importance on social issue of product or process [64], consensus has not reached on specific methodology for this category of sustainability assessment. Thus, in literature many researchers appraised various scoring systems for characterization of impacts. Some impact categories for SLCA are wage of foreman, human rights, health and safety, socio-economic repercussions, governance etc. Bork et al.

Table 2
Economic parameters, main economic assumptions and parameters for LCC analysis.

Parameter Value	*Amount Value (2017 PV)*	*Sources*
Inflation Rate	*3.4%*	*Malaysia Inflation Rate data*
Discount Rate	*4.5%*	*Malaysia formal Discount Rate data*
Electricity Cost	*38.53 Sen/ kWh*	*Malaysiakini data*
Transport	*0.31 MYR/* tkm	

[70] and Foolmaun and Ramjeeawon [68] methodology for SLCA was applied as “yes” or “no” corresponding to the measurement of semi-quantitative indicators. Similarly, Spillemaeckers et al. [69] used a method based on the fulfillment (1) or nonfulfillment (0) of the social indicators, and Zhao et al. [87] evaluated SLCA for green building and used interview method for collecting data for SLCA research. Escamilla (2016) conducted research on sustainability assessment and result shows in social category that bamboo creates more jobs than concrete in construction industry. A SLCA research accomplished by Hosseinijou et al. [86] in comparison between concrete and steel and result revealed that steel is the better option. Thus, the interview result by stakeholder shows that job creation in all stages of building such as construction, maintenance and disposal is very positive.

The aforementioned guideline (UNEP/SETAC) declared that “The ultimate objective for conducting an SLCA technique is to promote improvement of social conditions and of the overall socio-economic performance of a product throughout its life cycle for all of its stakeholders”. The assessment in this category contains two steps. First, assess the satisfactory rate of wage for workers and second, which material potentially could create higher number of job positions in Malaysia.

The main goal of the SLCA in this research is to analyze the stakeholder toward contribution to economic development for number of jobs created and its related amount of wage. The sufficiency of salary would be calculated by comparison of the amount of wage for construction worker (International Labour Organization) and the non-poverty wage based on non-poverty wage status (Sweatfree Communities, Non-Poverty Wages Malaysia) [56,57,60]. The non-poverty wage expresses the real living standard status more accurately and clearly than just displaying the GDP for worker. Based on the poverty guidelines announced by Malaysia's average national poverty, the non-poverty wage of other countries can be deduced by multiplying the United States’ non-poverty wage and the ratio of that country's GDP per capita to the United States’ GDP per capita (Sweatfree Communities. Non-Poverty Wages). This category is assessed in terms of the job positions that may be created by potential production of construction material for three conventional materials in Malaysia namely: wood, concrete and steel.

The social assessment was focused on the characterization of the employment generated by three different sector activities namely: timber industry, steel production and concrete factory. The analysis draws on the population of companies and organizations collaborating in the above sectors from 2010 to 2015. For confidentiality reasons, information at the company and worker level is not reported individually; hence data and results are aggregated into the aforementioned groups sector.

The criteria for wage of foreman has been investigated through detailed literature review related to Malaysian daily income. Then, pairwise comparisons among different social criteria have been made through formal interviews as suggested in the UNEP/SETAC guideline with some construction managers, workers, employees, local community, consumer and factory owner. Selected social criteria are discussed in the following sections. Company records, interviews with stakeholders involved in the processes and our observations during field visits were classified as specific data.

To evaluate the SLCA, the sample included 35 women (45%) and 40 man (55%) in an attempt to retain balance for gender distribution. In addition, the sample of interview can be regarded as representative of the population. The average age of the interviewees was nearly 45 years old. Of the participants, most were between 40 and 45 years old, about 65% was at the age range that people are likely to be potentially highly expensive on construction and materials as they have industry experience. Almost 15% of those interviewed were more than 55 years old, and the ratio of people between 35 and 45 and 45–55 years old was about 25%. The arrangement of age that has been chosen for the people who participated in the interview shows continuity, which was in accordance with the distribution of society. Also, the category of respondent included different responsibilities such as general staff (about 36%), self-employed (less than 39%), retired (about 16%) and management (about 9%). The stockholders who have been interviewed are from many different sectors and had been working in production of cement, steel distributing, wood plantation etc. This leads to their respondents’ or social acceptance of building material are universal. Limitations of the paper for investigation of social aspects is hindered by methodological limitations, and insufficient stakeholder integration are excluded from the study due to a lack of information. Therefore, other aspects could not be assessed at this time such as Fair competition, Forced labor or Child labor etc.

2.4. Case study

One of Malaysia's longstanding development objectives is the provision of affordable housing for Malaysians, with a focus on lower-income groups [29]. In the Eighth Malaysia Plan, the government planned to build another 131,300 units of low medium cost housing nationwide. Special attention must be given to low medium cost housing since majority of the Malaysian population is in this category [28]. Based on Syarikat Perumahan Negara Berhad, more than 60% of houses are single- story medium and low-cost housing in Malaysia. Therefore, it could be major contribution to control the GHG emission. A single-story residential building was assessed by wood, which based on previous research, is considered as lowest cost material in Malaysia than concrete. Fig. 1 represents the schematic model of the single-family house represented in Kuala Lumpur, the capital of Malaysia. The life span of the building is expected to be 50 years and the living area of the house is 155 m^2.

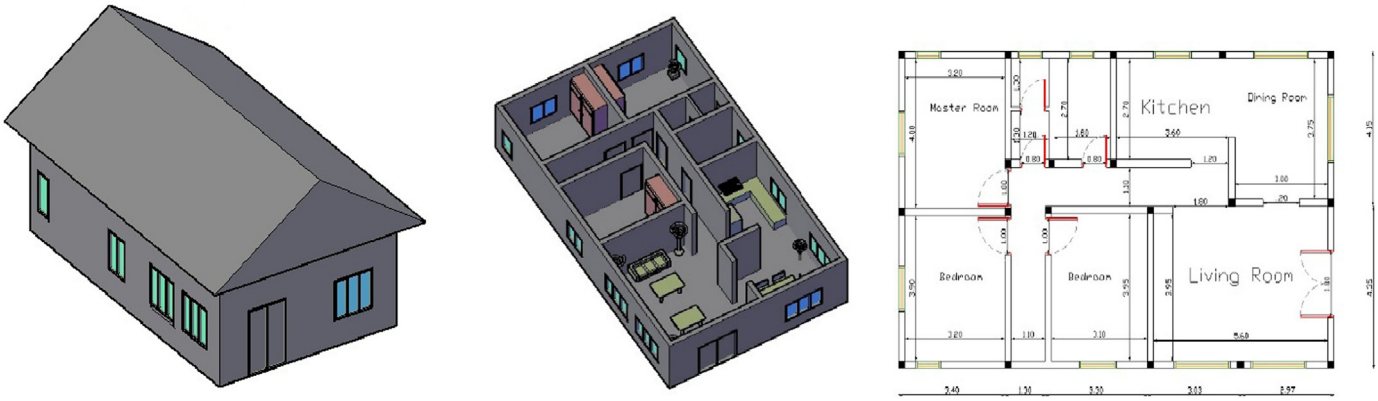

Fig. 1. Schematic model of the single-family house. a) With roof, b) interior and exterior walls.

In the previous hybrid timber structure, only global warming potential (GWP) has been assessed while in current study, other environment indicators for building construction such as AP, AE, FD, HTP are considered in order to obtain a full result for environment.

All previous studies address use of timber or timber structure to obtain environment emission mitigation, however other study declared that timber life span was normally less than other alternative material ([6,7]) and began to introduce new structure for timber building. However, there is no reference to address which structure by timber is optimum choice for house builder. The disadvantage of common timber structure is failure through excessive deformations; transformation of the structure into a mechanism; rupture; loss of stability. Kadir and Balasbaneh [8] and Balasbaneh and Kadir [5,6,7,35] introduced new structure containing wood with other building material mostly as composite to encourage use of wood into building scheme. The case study for current research was extracted from above research. But the gap as to what kind of timber structure can be the best option for house maker remains. Their cost and social impact is also unclear. Therefore, finding the optimal structure containing wood components requires emergent plan.

Hybrid construction maximizes the structural and architectural advantages in combining components made of different materials. In hybrid construction, the different materials may work together or independently, but will always provide advantages over the use of a single material [11]. Five types of building scheme have been choosing as hybrid construction, all containing wood, toward finding the best option as construction material. As shown in Fig. 2, all case studies are based on hybrid and wood-based materials. The number of traditional timber houses has been gradually decreasing in Malaysia for the past 40 years, with almost all new construction built by alternative material other than wood.

2.5. Data collection

The case studies are all new methods of construction that attempt to have a maximum wood in their components. This research assessment has focused on merging modern structure with traditional building material practices and components are all assumed to be fabricated at the factory. As a renewable resource which stores carbon, wood can play a significant role in terms of providing a solution to reduce the environmental impact of urban densification.

The initial data for assessment had been gathered from variety of sources such as visiting the manufacturing and saw mill. Transportation for material has assumed the use of lorry, with Malaysian average characteristics and the related inventory data with those processes have been obtained from Refs. [90,76].

In order to model the environment impact for building scheme, this assessment is comprised of a few steps that gather all the features, including emission from plantation and raw material extraction; manufacturing; emission for maintenance; and emission from transportation.

CO_{2eq} emission from recycling or landfill building material after demolition in end of life cycle of building. The transportation data were calculated based on impact per ton kilometre (t km) fleet average from the Ecoinvent database with adaptation of Malaysian data from MYLCID for electricity and diesel.

In this study, the following scenarios are assessed: The first structure as seen in Fig. 2 is hybrid construction. Hybrid construction with precast concrete (T1) means combined use of precast concrete with timber, cast in situ concrete, for the benefit of the building process at large. The definition of structure is as the post and beam are fabricated as precast concrete while all external and interior walls have been made from prefabricated timber. The process for acquiring the material are the raw materials which are the oil palm trunks and tropical wood and the energy from diesel and electricity from grid which is mainly used for the drying process. Ahmad et al. [37]. For drying processes, factories use kiln drying processes. The inputs are mainly electricity, water consumption for boiler, diesel consumption for traction, urea formaldehyde, tropical wood veneers etc. End of life assumed 100% landfill for concrete and for wood, 60% generate electricity and 40% reuse. The cost of concrete ready mixed concrete, grade 30 (normal) is around 210.00 RM/m^3, although depending on the grade, it could vary between 170 and 240 RM/m^3.

The second structure (T2) is a combination of steel stud covering beam and column to obtain stronger component to have a higher life span in tropical area. Similar to T1, all exterior and interior walls have been manufactured from prefabricated timber. Integrating steel and wood, by using a combination of pre-fabricated steel trusses and wood framing, building owners can benefit from the strength, durability and clear spans offered by steel, with improved insulation performance offered by wood. In the case of the steel frame, steel was assumed to be 100% recycled [34,43]. The density of steel was estimated as 7800 kg/m^3. To assemble the wall components, some other machinery has been used such as crane and air compressor, which have already been assessed as construction process. The thickness of steel stud which covered surrounding of wood in main structure is estimated as 0.02 m, with 0.15 m width and specific weight of 12 kg/m^2. The distance of transportation is also estimated as 30 km for both mill to site and from site to the disposal scenario and Lorry 40 t has been chosen for this process (Table 3).

The LCI for the manufacturing and production of steel stud in T2 (also in all other steel stud on other structures) was calculated based on MYLCID database to achieve the most accurate result for local data. The energy requirement of 1 M^3 steel production stage has been assumed to use 79,732 MJ of natural gas, 23,876 kW electricity, 61 L of diesel and 139.8 L of gasoline. No maintenance has been assumed for steel in all

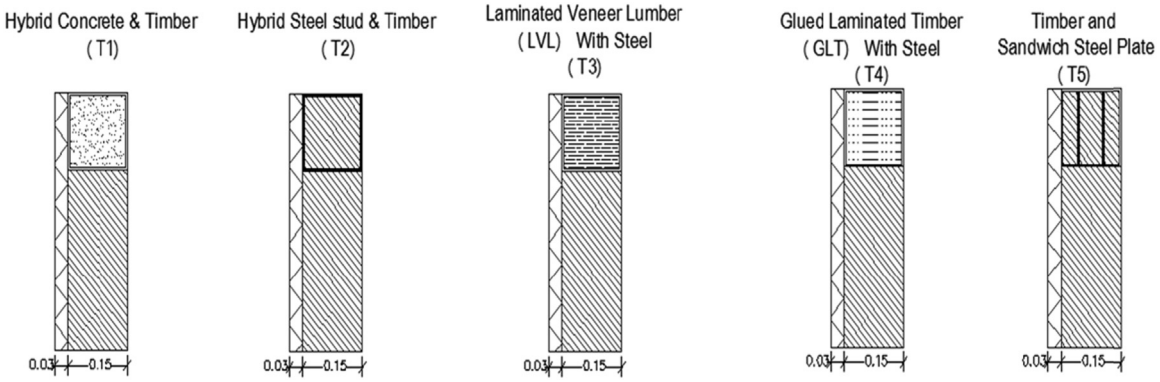

Fig. 2. Hybrid Concrete & Timber (T1), Hybrid Steel stud & Timber (T2), Laminated Veneer Lumber (LVL) With Steel (T3), Glued Laminated Timber (GLT) With Steel (T4) and Timber and Sandwich Steel Plate (T5).

Table 3
Description of base-case building components.

Buildings components	building scheme	wall components	Thickness (m)	Transportation	Total weight (kg)
Hybrid Concrete & Timber	*T1*	*Wood wall*	0.15	*Lorry 40 t, 30 km*	*29,276*
		Concrete	0.15	*Lorry 16 t, 40 km*	*2939*
		Screw		*Passenger car, 5 km*	*34*
Hybrid Steel stud & Timber	*T2*	*Wood wall*	0.15	*Lorry 40 t, 30 km*	*32,433*
		Steel	0.020	*Lorry 16 t, 40 km*	*1848*
		bolt		*Passenger car, 5 km*	*34*
Laminated Veneer Lumber (LVL) With Steel	*T3*	*Wood wall*	0.15	*Lorry 40 t, 30 km*	*29,276*
		Laminate veneer lumber	0.15	*Lorry 16 t, 45 km*	*5400*
		Stainless Steel	0.020	*Lorry 16 t, 40 km*	*1848*
		bolt		*Passenger car, 5 km*	*35*
Glued Laminated Timber (GLT) With Steel	*T4*	*Wood wall*	0.15	*Lorry 40 t, 30 km*	*29,276*
		Glued laminate timber	0.15	*Lorry 16 t, 50 km*	*6200*
		Steel stud	0.020	*Lorry 16 t, 40 km*	*1848*
		Bolt		*Passenger car, 5 km*	*35*
Timber and Sandwich Steel Plate	*T5*	*Wood wall*	0.15	*Lorry 40 t, 30 km*	*32,433*
		Steel sheet	0.040	*Lorry 16 t, 40 km*	*2148*
		bolt		*Passenger car, 5 km*	*34*

scenarios during the life span of building. Finally, at the end of building life, the steel stud would be assumed to be totally (100%) recycled [91]. All structures in this research which have steel (T3, T4 and T5) have been assumed to have a same process as T2 for their steel material.

The third building structure was integrated from Laminated Veneer Lumber (LVL) With Steel stud (T3) which is a combination of LVL covered by 2 mm steel stud used as post & beam while all building walls are assumed as wood prefabricated timber wall. The raw density of the LVL is about 590 kg/m^3 and LCI data of LVL manufacturing and production of the structural wood was sourced from the MYLCID and Ecoinvent Database [39]. While wood fuel constitutes up to 80% of the total energy requirement, the remainder is sourced from natural gas and electricity. The dried veneers are then glued using adhesive and pressed to form LVL products [41]. Finally, the LVL products are sent to a finishing area for trimming and sanding.

The fourth structure is Glued Laminated Timber (GLT) covered with Steel (T4), which is the same as previous scheme that is a combination of engineering wood and steel used as main structure, while all building material was designed from prefabricated timber. Glume applied in post & beam and its raw density is 850 kg/m^3. The last scheme is T5 and the size of beam and column is 3*0.15*0.15 m with normal density of Malaysia timber 810 kg/m^3. The post and beam are integrating Sandwich Steel Plate with wood. The wood material was transferred by Lorry 40 t, 30 km away from site. End of life for wood (40%) has also been applied for re-use and the rest (60%) incinerated for energy recovery and used as fuel to produce electricity. When wood products are burned for energy production, the carbon is emitted but the energy produced displaces fossil fuels that therefore remain in storage, resulting in emission reductions. This scenario has been assumed same for all structures as their end of life scenario for wood.

3. Results and discussion

The aim of this research is to assess hybrid timber scheme in Malaysia. Result of LCA, LCC and SLCA have been represented in three categories as following. This assessment covered this gap using case study buildings for the Malaysian construction building. The goal of this research is to assess which types of timber housing should be promoted for Malaysian building toward achieving higher sustainability.

3.1. Environment impact

The result of LCA has been represented in Fig. 3 and Fig. 4 and the details of contributions of the emissions to each impact factor of the five hybrid timber structure assessed scenarios. The main reasons that hybrid construction is increasingly desirable is to improve occupant and environmental safety with low demand for maintenance. On the other hand, using the full amount of concrete in the building has increased the CO_{2eq} emission and excessive environment impact from this sector.

The only hybrid structure containing concrete (T1) had largest environment impact in all categories. The structure combining the GLT with steel surrounding T4 it shows the second highest environment pressure except for FDP where T3 represent the second higher emission in this category by 4.65E + 3 kG oil eq. the third highest emission came from T3 structure where LVL combined with steel stud in structure along with timber wall. Although T3 has been shown less impact compare to T4 but in all category represent almost close amount to T4 except for acidification category where there is a high difference. Overall T2 option was the second best performance in all environmental impact Categories compare to T1, T3 and T4. On the other hand, T1 option has shown the lowest environmental burdens in all categories.

As shown in Fig. 4, T1 concrete has poor performance in this structure which is attributed to excessive energy demand for concrete manufacturing process, specifically emissions needed for cement manufacturing process as well as extensive materials and transportation. The result shows more than 40% of emission for T1 is related to energy consumption during manufacturing, which is valid for all other structures as well. The second major contributor to emission is the process for material extraction for concrete and plantations and harvesting related to trees. The third major contribution to emission is the final disposal for concrete which leads to landfill and its transportation, while the emission in HTP for landfill is the highest. Despite the concrete, for end of life scenario of wood, the energy recovery has positive impact on environment. The result shows energy recovery contributed approximately 19% in GWP, and 3%, 4%, 6% and 2%, respectively, for AP, EP, FDP and HTP.

The remaining structures had not been built by concrete, while all of them had been built with some steel in their structures, as steel has less impact to environment due to its final disposal where it is going to be recycled. T2 major contribution to environment impact is related to steel extraction and production stages which contributed more than 50% of all emission. The other categories such as transportation and maintenance, has a negligible impact. On the other hand, steel recycling has a positive impact on environment where wood disposal for generating electricity has same impact. In fact, steel disposal shows better performance in all categories while timber positive impact is high except in AP. The advantage of recycling material such as steel is to reduce energy requirement compared to virgin steel. The result shows recycling is reduced approximately 22% in GWP, 17% in AP, 18% in both EP and FDP and 14% offset to the HTP impact, respectively.

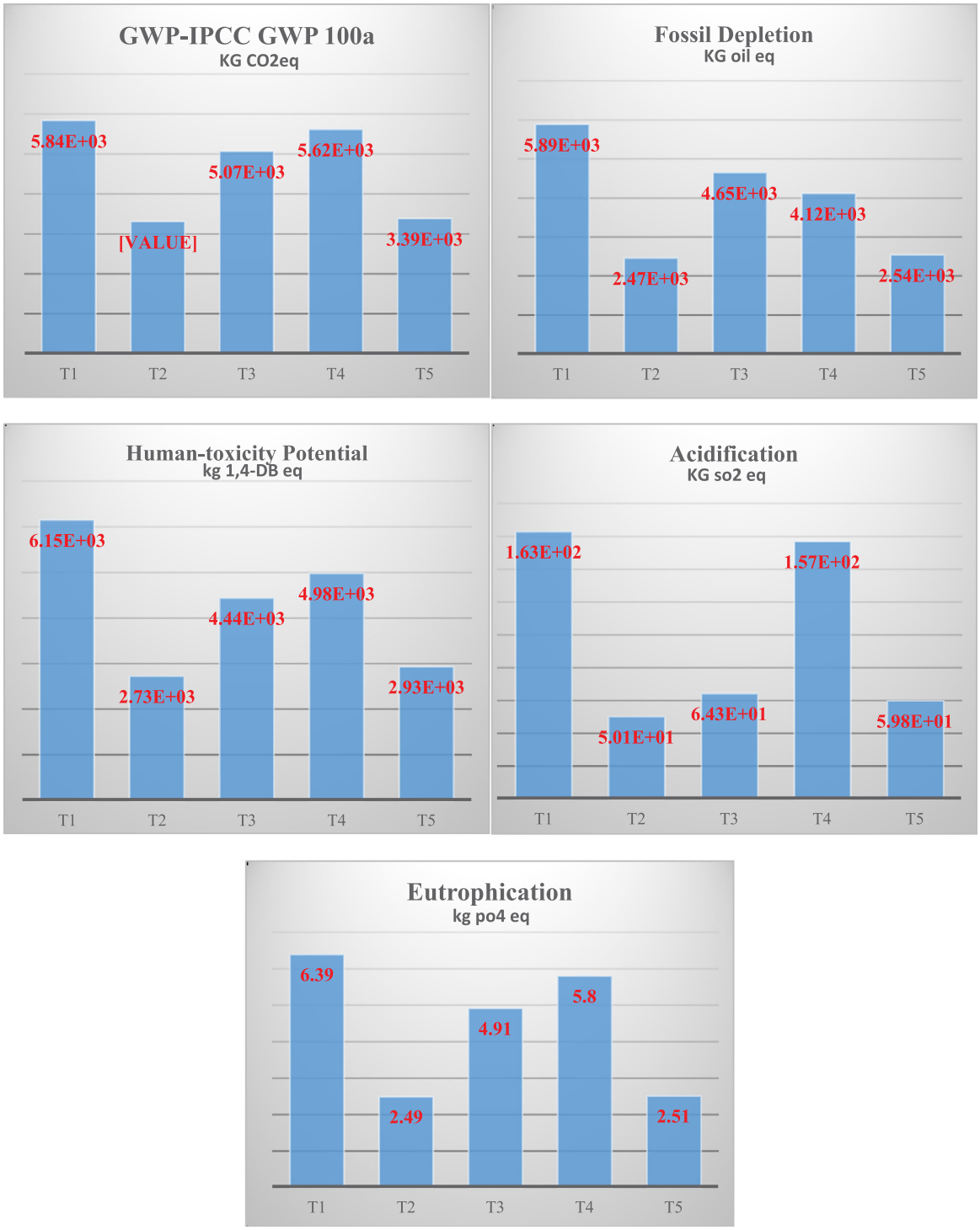

Fig. 3. LCIA results analysis for different categories, Hybrid Concrete & Timber (T1), Hybrid Steel stud & Timber (T2), Laminated Veneer Lumber (LVL) With Steel (T3), Glued Laminated Timber (GLT) With Steel (T4) and Timber and Sandwich Steel Plate (T5).

It is notable to mention that T2 has been shown as lowest emission in all categories namely: 5.84E + 03 kg CO_{2eq} in GWp, 5.01E + 01 kg so2 eq in AP, 2.49 kg po4 eq in EP, 2.47E + 03 kg oil eq in FDP and 2.73E + 03 kg 1,4-DB eq in HTP. The third structure is containing of LVL with steel which has relatively high HTP impact. These impacts are related mostly to the use of preservative operation for manifesting and resin production stage, in which 56% of this structure contributed only to manufacturing and production in HTP. In previous research [92] the production of engineering wood as well as end of life scenario were pointed out as the major resource contributors to the environmental impact. Maintenance and transportation showed relatively minimal impact in all categories to the environment. Additionally, preservative operation of LVL has shown the lowest impact in EP. The end-of-life stage contributes with a negative value, i.e., this stage turns out to have a beneficial influence due to steel recycling and timber disposal treatment options. Therefore, incineration of wood helps to reduce environment impact due to also reducing fossil fuel for power generation.

Thus, more than 34% reduction of GWP, 17%, 20%, 32% and 11% reduction potentially realized during energy recovery during the end of life of T3 structure respectively for AP, EP, FDP and HTP. Meantime, the

Fig. 4. Life cycle environmental emissions sources.

emission related to T3 are 5.07E + 03 kg CO_{2eq} in GWP, 6.43E + 01 kg so2 eq in AP, 4.91 kg po4 eq in EP, 4.65E + 03 kg oil eq in FDP and 4.44E + 03 kg 1,4-DB eq in HTP. According to IPCC (2007), CO_2 from burning biomass (wood waste) were not counted towards the GWP.

The fourth structure is a combination of GLT surrounded by steel-T4. Similar to the previous structure (T3), steel T4 has a high emission in HTP category, mostly for its GLT production. Comparing LVL option in T3 with GLT in T4 structure shows raw material from low value logs for LVL production contributed to the lower environmental impact than mature hardwood log that been used to produce GLT. This leads to relatively lower emissions during the plantation stage and shorter harvesting cycle and allocation of a higher proportion of the emissions to the final harvest, which has a higher value. Therefore, the production of LVL has released less emission to environment particularly on GWP that was reduced by 14% and in other categories AP, EP, FDP and HTP reduced by 4%, respectively. The other categories such as transportation, maintenance and end of life are almost same as T3. Meantime, the emission related to T4 are 5.62E + 03 kg CO_{2eq} in GWp, 1.57E + 02 kg so2 eq in AP, 5.8 kg po4 eq in EP, 4.12E + 03 kg oil eq in FDP and 4.98E + 03 kg 1,4-DB eq in HTP.

The result from Fig. 3 shows that the T5 is the second best option for hybrid timber construction. The main differences between T5 and T2 is relatively back to the quantity of steel that has been applied in their structure. The steel weight on T5 is quite heavier than in T2. T5 major contribution to environment impact is related to steel extraction and production stages which contributed more than 55% of all emission. Like T2, the transportation and maintenance has a negligible impact on environment emissions. The second major source of emission is related to the wood plantation and manufacturing, which contributed around 25–30% to the environment. In the end of life scenario, steel recycling and wood incineration both have a good impact, with the result showing steel recycling reduced approximately 22% in GWP, 15% in AP, 18% in both EP and FDP and 14% offset to the HTP impact, respectively, and the wood incineration shows 16% reduction in GWP, 6% in AP, 13% in both EP and FDP and 9% offset to the HTP impact. Meantime, the final emission related to T5 are 3.39E + 03 kg CO_{2e}q in GWP, 5.99E + 01 kg so2 eq in AP, 2.51 kg po4 eq in EP, 2.54E + 03 kg oil eq in FDP and 2.93E + 03 kg 1,4-DB eq in HTP.

3.2. Life cycle cost

The result of LCC of five different scenarios represent that the LCC values are in agreement with the environmental performance of the options, as shown in Fig. 5. The result of LCC for T1 indicated that the structure containing concrete is the most expensive option among all structures with 222,510 MYR. This is because concrete requires large quantity of materials which need heavy machinery for handling heavier materials with more processing elements which normally contribute to higher cost maintenance, demolition etc. On average, manufacturing and construction contributed 79%, maintenance 15% and disposal 6% to the total LCC. Table 4 shows the cost for all categories for all structures namely: Construction, Maintenance, End of life scenario and Revenue for wood and steel for different material, with incineration at the end of life for wood, recycle for steel and landfill for concrete.

All structures in this study are strong against load bearing and displacement. Humidity is considered the main threat to those with external wood wall due to tropical conditions. Therefore, maintenance phase can play critical role in considering sustainability and therefore, maintenance is higher than Demolition & waste management stages.

The main cost is related to first phase which is raw material provision, construction and transportation of energy resources including raw material and equipment for material. Construction cost is consisting of manufacturing, labor, transportation and installation cast. T1 not only has a highest total cost but also contributed to highest manufacturing and construction cost among other structures. This is related to higher cost of concrete that requires more energy usage from fossil fuel attributed to electricity and natural gas consumption. The

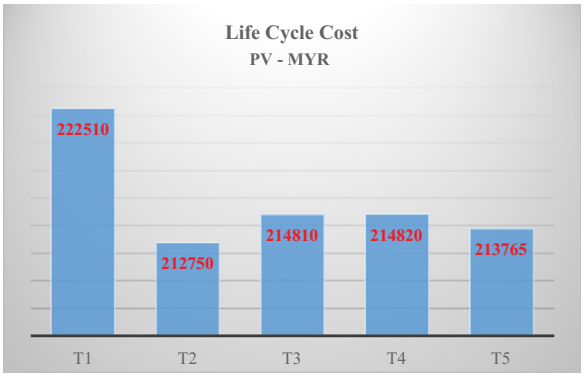

Fig. 5. life cycle cost scenario for Hybrid Concrete & Timber (T1), Hybrid Steel stud & Timber (T2), Laminated Veneer Lumber (LVL) With Steel (T3), Glued Laminated Timber (GLT) With Steel (T4) and Hybrid double Sandwich Steel Plate & Timber (T5).

Table 4
LCC of houses designs-wall assemblages.

Structures	*Construction*	*Maintenance*	*Demolition & waste management*	*Revenue-recycling*	*Revenue -energy recovery*
T_1	*195539*	*28926*	*6810*	–	*8765*
T_2	*173327*	*40422*	*8510*	*259*	*9250*
T_3	*177132*	*38665*	*8592*	*259*	*9320*
T_4	*177160*	*38667*	*8592*	*259*	*9340*
T_5	*174115*	*40615*	*8550*	*270*	*9245*

construction cost of wood walls and concrete post & beam (T1) are respectively equal to 157,781 MYR and 37,758 MYR. This has revealed that despite the quantity of concrete being much less than timber, the cost is not low. T1 maintenance is also less compared to other structures while end of life cost is higher due to landfill of concrete.

The LCC's for manufacturing of steel in t2 is 6556 MYR and 166,771 MYR for wood wall panel and structures. The costs of energy consumption, materials as well as labor and manufacturing facilities were all included. However, the quantity of steel stud in three structure T2, T3 and T4 are the same, therefore the cost for construction and their Revenue- recycling would be the same. Hence, *259* MYR would be paid back for recycling each functional unit of steel stud. The construction cost for T3 and t4 is literally higher than T2 and T5 due to the use of engineering wood (GLT and LVL) in their structure as post and beam covered by steel stud. The cost of wood walls and LVL in T3 are, respectively, 157,781 MYR and 12,759 MYR and the cost of wood wall and GLT for T4 are 157,781 MYR and 14,823 MYR. The construction cost for wood material and steel stud in T4 were equivalent to 167,761 MYR and 9354 MYR, respectively. This shows that the construction cost of steel in T5 is a little higher than other structure, which is related to its higher quantity. Therefore, the construction stage was identified as the highest LCC phase in all other structures.

3.3. Sociocultural category assessment

Both developing and developed nations have realized and understand the significance of construction sector in socio-economic and sustainable development of a country. Among all three sustainability dimensions, the social cultural is the least developed and even lacked standardization until recently. Thus, the first standard of SLCA, EN 15643-3 [49], was published in 2012. Malaysia as one of developing nation has a massive number and quantity of construction in the last few decades and over the last two decades, construction has been contributing between 3% and 5% of the aggregate economy GDP.

In this study, capacity for job creation, salary status, aesthetics, suitability to location, health and safety and local supply were identified as main social impact indicators. Due to compliance of wall materials considered in this study, the main components, which were wood, health and safety, were found to make no contribution to differentiating different alternatives and was excluded from the analysis. The view towards beauty of a particular façade system may vary considerably from a person to another, rendering aesthetic a highly subjective indicator. In this case, since only the structure is different between alternatives, the study assumed that aesthetics from façade would be the same in all case studies, so it can be neglected from the analysis. On the other hand, wooden building has been one of the prominent structures in tropical area and therefore, suitability to location has already been proven. On the other hand, due to direct impact of local supply on reducing the transport costs, which have been already considered, local supply was excluded to avoid repetition. The remaining selected measures are discussed in the next subcategories.

3.3.1. Salary status – poverty impact for construction foreman

The first step of survey it assessed whether the wage of this sector is

suitable or not. Household income Survey (HIS) and Poverty Line Income (PLI) statistics are used for policy formulation and development planning particularly for the poverty eradication programmers and strategies for distribution of income. The statistics provided were referred from Post Enumeration Surveys, Agriculture Census, Household Income Surveys and statistical compilations. According to the GDP per capita data (website) and the non-poverty wage calculating method, the non-poverty wage for Malaysia in January 2017 is deduced as around 1200 MYR.

The labor wage rates for general construction worker in building industry for local citizens in January 2017 was 2865 MYR. Since the average monthly salary of foreman is much higher than the current estimated non-poverty wage (approximate two times more), it is believed that construction worker's salary status is still sufficient to support their living via the aforementioned. Basically, working in timber constructing site offers a slightly higher wage for worker who has less income monthly. For example, daily salary for timber component is 97.20 MYR versus 84.30 MYR for light gauge steel.

3.3.2. Capacity for job creation

At present, there is a vital need to assess the social impact of product or material in order to enable better selection of sustainable material to potentially inform the affected stakeholders to be aware of their choice, especially in construction building. The base material of all case study in this research consist of wood and the big differences are related to the main structures, which motivated the idea to build strong scheme for building which has a higher life span with minimum maintenance compared to solid timber and, on the other hand, to encourage construction industry to use wood those structure, has been assessed. This is because declining demand for wood, especially in construction sector, will reduce investment in sustainable forest management by governments [42], industries and stockholders, adversely affecting future wood supplies and environmental services.

The interviews are conducted to identify which material (timber, concrete and steel) can create higher job possibility for low income community. A substantial amount of data about the key social issues has been collected. The result of survey from current research is toward programs planned to help low income households increase their earning potential. The result of survey shows the number of workers who are collaborating in wood industry is much higher than alternative material and this is related to higher procedures for wood production and harvesting such as estate management, forest planning and approval, seedlings, layout of planting, fertilizer application, thinning process, land cost till it is processed in mill.

The interview assessment accomplished five categories of job creation stages as follows: Raw material acquisition, production and construction material, construction, maintenance demolition recycle. From a SLCA perspective, it can be concluded that wood performance compared well to steel and concrete. The wood shows the highest job creation on raw material acquisition, production and construction material, construction and also maintenance phase with more than 55% of interviewers responding. The second position is related to steel with 30% of respondents and the production and construction material and demolition recycle showed the highest possibility for job creation compared to other alternatives. The last material to consider in terms of job creation was concrete, with only 15% of respondents supporting it. The production and construction material was the highest possibility stage to creation for job related to this material. Wood product instead of cement, concrete and steel could have a positive role in the economic stabilization efforts, particularly through job creation and the rebuilding of the natural capital base [42]. Thus, increasing use of wood in construction can help to eliminate deforestation. This is particularly true for tropical forests and especially where more profitable land-use options are available. One additional advantage is that after the period of establishment of the wood plantation, the communities can extract yearly harvest of 15% of the standing wood and this means that the communities can have a steady income every year. Wood industry associated with timber Companies employ more workers than other companies in the Malaysia economy, and steel and concrete, unlike timber, create low level of job creation.

3.4. Discussion – sustainability assessment

Until 40 years ago, timber was typically used as building material in Malaysia due to low initial cost, natural insulation properties and ease of transport. After that alternative material replaced in construction such as concrete. This trend occurred due to some mechanical failure on timber structure, thereby reducing its life span [6].

Therefore, to encourage use of wood in construction, some previous research advised that new structure should be constructed with an eye to greener production and sustainability. In those research, only GWP of new structure had been assessed while the gap of new structure available for other categories was related to environment such as AP, EP, FDP, HTP, the cost of each new structure and finally the SLCA. The result shows these gaps by finding the quantity and differences between these case studies.

The advantages of hybrid timber structure over timber only structure is higher life span and less attention to the maintenance phase which leads to both saving environment impact and cost for house owner. Therefore, hybrid timber structure might have a lower primary cost than timber only structure, but over the whole life span of building, it would be cheaper [36]. Thus, the steel and concrete that combine with wood structure have relatively no need for maintenance cost [82], consistent performance and long lifespan. According to the results, timber structure with concrete (T1) in it as post & beam had the highest environmental emissions in all categories namely: GWP, EP, AP, FDP and HTP mainly due to the significant production of concrete and cement material and energy intensity during the manufacturing process. The second highest emission is related to the timber structure that combined GLT with steel as hybrid lifelong span scheme. T4 has shown higher emission in all categories except FD which was lower than T3 structure. The most significant environment impact of T4 structure are related to resin and adhesive process for GLT production, followed by steel manufacturing and energy consumption in the whole life cycle. However, this research assumed all steel stud (100%) had been recycled in the end of life of building which contributed significantly to GHG emissions offset.

Among all alternatives, T2 represented the best option due to releasing the lowest emission in all environment categories and therefore, it could be replaced by current construction method in Malaysia. On the other hand, T2 cost was the lowest among other structures due to lack of concrete in its structure or any engineering wood plus recycling of steel in the end of life of building. The result showed that the wage accommodation for foremen, while using profitable material toward creating jobs in Malaysian society. Thus, this would be a supporting decision toward applying wood in building construction not only to support worker community and to create higher number of jobs, but to move forward toward greener buildings. Not only do timber buildings have advantage in its SLCA over other material for construction, house containing wood can accelerate the number of jobs created in low income society. Consequently, for lack of high literature, the result shows that wood in construction has not only higher wage for worker but can create higher number of jobs for this industry compared to other alternatives such as concrete or steel for its longer growing process. Future work could be assessing each timber composition on more SLCA assessment issues and also some other environment subject such as carcinogen or ozone layer depletion. In other hand their load bearing can be assess in order to compare it with other beam.

4. Sensitivity analysis

There is no doubt that wood is currently the best material in

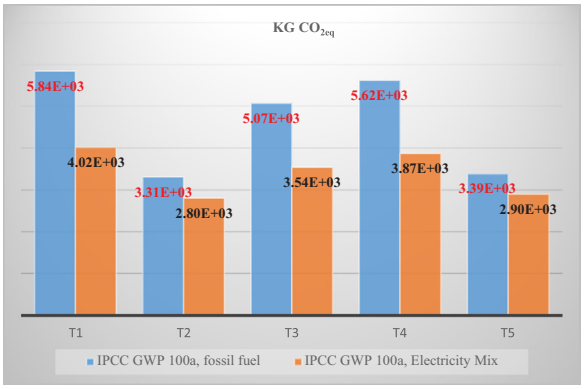

Fig. 6. Sensitivity analysis for electricity of manufacturing material with different scenario.

building construction toward diminishing CO_{2eq} emission compared to alternative material such as concrete or brick. Many timber structures have been introduced and built throughout the world. This research assesses the sustainability view of each building scheme. Sensitivity analysis were carried out considering below electricity factor.

4.1. Electricity mix toward CO_{2eq} emissions

Based on United Nations Environment Programme (UNEP; www.unep.org), 1/3 of all global greenhouse gases come from buildings. Climate change is the most serious global sustainability issue. At present, the significant challenge for humanity is to how decrease the high greenhouse (GHG) emissions from different sources to control and decrease global warming. Climate change caused by greenhouse gas emissions will fundamentally change the way that people live and do business [62]. Carbon dioxide is a gas related to serious environmental problems with a reflection on human health. It is one of the main greenhouse gases [45] and responsible for the global temperature increase observed in recent years [46]. One of the biggest contributors towards the production of material in Malaysia is related to the electricity used in this country. The electricity that is assessed for all material production in factory (sawmill), process for resin the engineering wood, concrete production or steel had already been considered as fossil fuel consumption. The electricity generation in Malaysia is allocated as 96.63% from fossil fuel based on latest report on 2015. Fig. 6 shows the result of sensitivity analysis.

Electricity generation in Malaysia places a significant burden on GHG and other emissions to environment every year. The alternative, electricity, has been assumed at this stage, therefore, electricity used had changed to hydro power to determine the differences and effect of the depletion of fossil fuels. In addition, it will be clear how the result could change if the production of construction material imposes a burden on the environment in different countries. To compare the result of this research and find the improvement of electricity mix with only using fossil fuel, the share of 70% hydropower, like that used in other country such as Brazil, has been chosen.

Based on latest measurement by the Climate Change Performance Index 2018 (CCPI), Malaysia's ranking dropped from 57th to 52nd, and this put Malaysia in red zone in the rating of very low control of their GHG emission, or, in other words, an increase in climate emissions. This occurred after Malaysia had decided to decrease its CO_2 emission and other GHG emission by 40% by 2030. Therefore, the government not only must encourage the use of wood (due to its lower environment impact and cost), but must change its energy usage for electricity to decrease its CO_2 emission.

Fig. 6 shows the result of variance for applying different scenario. The new electricity trend combined with hydropower shows about 15–30% deduction on CO_2 emission for each structures. This is due to the lower amount of CO_2 emissions that can be avoided from a "low CO_2 emitting" electricity mix. Nevertheless, under this condition a positive impact can still be potentially produced in both the environment and the economy. The sensitivity analyses showed that by changing the different electricity application or mix, the CO_2eq emission can be significantly reduced in Malaysia.

5. Conclusion

The sustainability product for government has become as a major concern around the world recently. There has been some encouragement lately from both previous literature and public organization to use wood material in the building industry in both developed and under developed countries due to its reasonable cost and low environmental impact in comparison with alternative materials. In this study Life cycle assessment, costing and social assessment has been implemented to appraise the impacts of different hybrid timber structure selection of residential sector. This research focuses on identifying the appropriate hybrid wooden structure that can provide all necessary requirement for having better residential building. The aim of this research is to create best option toward low medium cost housing with attention to job creation. Thus an increase in the number of planned housing units will rebound in an increase in potentially created job positions.

The result of environment impact shows that the manufacturing sector has been generating higher impact on environment. In addition, T2 is the best option due to elimination of using concrete in its structure and applying the highest possible percent of timber. The recycling of steel has a positive impact on environment in both environment and cost aspect. The result shows that in GWP, the emission from T2 is around 25–40% lower than T1 or T4, where concrete or engineering wood had been used their structure (post & beam). For FDP, EP and HTC the outcome shows even higher differences between T2 with T1 and T4 where the variance is between 40% and 55%. In AP category, the result shows that T2 has a profound difference from T1 and T4 of about 60%, while it varies from T3, which contains of LVL in its structure (post & beam), is much lower than the other two structures. In all environment assessments categories, T5 has been higher than T2 by about 5–8%, which makes it the second best option in environment category.

T2 is also the best option in full LCC. Finally, to encourage the industry to use wood, the SLCA result shows that timber can create a higher number of jobs and therefore, it could even help low income categories by offering steady job, thus steel is allocated in the second option to creating job. The finding of this research is that timber is not only suitable for low medium cost building but building with wood can create more job position for workers. Therefore, the result of this study can help persuade the government to make a policy toward sustainability for construction sector.

References

[1] European Commision, "2030 climate and energy framework," [Online]. Available: ⟨http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm⟩. (Accessed 2016).
[2] Trends in global CO2-emissions. 2016 Report, ⟨https://www.google.com/url?Sa=t&rct=j&q=&esr c=s&source=web&cd=7&ved=0ahUKEwip1pmQkffWAhXQKFAKHVobDzIQFghLMAY&url=http%3A%2F%2Fedgar.jrc.ec.europa.eu%2Fnews_docs%2Fjrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf&usg=AOvVaw1EekZzG-MCaDLxE4Q7GPwr⟩.
[3] S. Shahid, Vulnerability of the power sector of Bangladesh to climate change and extreme weather events, Reg. Environ. Change (2012), https://doi.org/10.1007/s10113-011-0276-z.
[4] C. Kibert, Sustainable Construction: Green Building Design and Delivery, 2nd ed., John Wiley and Sons, New Jersey, 2012.
[5] A.T. Balasbaneh, B.M. Kadir, Life cycle assessment of IBS in Malaysia and comparing human health on timber and concrete pre-cast, Res. J. Appl. Sci., Eng. Technol. 6 (24) (2013) 4697–4702.
[6] A.T. Balasbaneh, B.M. Kadir, Proposing of new building scheme and composite towards global warming mitigation for Malaysia, Int. J. Sustain. Eng. (2017) 1–20, https://doi.org/10.1080/19397038.2017.1293184.

[7] A.T. Balasbaneh, B.M. Kadir, Strategies for reducing greenhouse gas emissions from residential sector by proposing new building structures in hot and humid climatic conditions, Build. Environ. (2018), https://doi.org/10.1016/j.buildenv.2017.08.025 In press.

[8] B.M. Kadir, A.T. Balasbaneh, Combinations of building construction material for residential building for the global warming mitigation for Malaysia, Constr. Build. Mater. 85 (2015) 100–108, https://doi.org/10.1016/j.conbuildmat.2015.03.083.

[10] Housing and Population Census Malaysia, Institute of Southeast Asian Studies. International Association of Certified Home Inspectors, 2010. InterNACHI's Standard Estimated Life Expectancy Chart for Homes, (2016), 〈https://www.nachi.org/life-expectancy.htm〉. (Accessed 29 March 2016).

[11] J.N.J.A. Vambersky, Hybrid structures – synergy with precast concrete, Delft University of Technology, The Netherlands, in: Proceedings of 25th Conference on Our World in Concrete & Structures: 23–24 August 2000, Singapore.

[12] I. Sartori, A. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: a review article, Energy Build. 39 (2007) 249–257.

[13] G. Battle, Ropemaker place calculating an office's lifecycle carbon footprint, Chart. Inst. Build. Serv. Eng. J. (2010).

[14] Eline Himpe, Leen Trappers, Wim Debacker, Marc Delghust, Jelle Laverge, Arnold Janssens, Jan Moens, Marlies Van Holm, Life cycle energy analysis of a zero-energy house, Build. Res. Inform. 41 (4) (2013) 435–449, https://doi.org/10.1080/09613218.2013.777329.

[15] R.A. Khan, M.S. Liew, Z.B. Ghazali, Malaysian construction sector and Malaysia Vision 2020: developed nation status, Procedia - Social. Behav. Sci. 109 (Supplement C) (2014) 507–513.

[19] T. Goverse, M.P. Hekkert, P. Groenewegen, E. Worrell, R.E. Smits, Wood innovation in the residential construction sector; opportunities and constraints, Resour. Conserv. Recycl. 34 (2001) (53e74).

[20] C. Martins, P. Santos, P. Almeida, L. Godinho, Dias A. Acoustic performance of timber and timber-concrete floors, Constr. Build. Mater. 101 (Part 1) (2015) 684–691.

[21] H. Islam, M. Jollands, S. Setunge, I. Ahmed, N. Haque, Life cycle assessment and life cycle cost implications of wall assemblages designs, Energy Build. 84 (2014) (33e45).

[22] ISO 14040, 2006. Environmental Managemente Life Cycle Assessment- principles and Framework, second ed. International Standards Organisation (ISO 14040), Switzerland.

[23] S. Kim, J.-H. Moon, Y. Shin, G.-H. Kim, D.-S. Seo, Life comparative analysis of energy consumption and CO_2 emissions of different building structural frame types, Sci. World J. 2013 (2013).

[24] N. Hossaini, B. Reza, S. Akhtar, R. Sadiq, K. Hewage, AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver, J. Environ. Plan. Manag. 58 (2015) (1217e1241).

[25] RayLua Hangyong, Hanandeh liEl, P.Gilbert Benoit, A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: environmental and economic perspective (10 November), J. Clean. Prod. 166 (2017) 458–473.

[27] B. Basaglia, K. Lewis, R., Shrestha, K., Crews, A comparative life cycle assessment approach of two innovative long span timber floors with its reinforced concrete equivalent in an Australian context. in: Proceedings of International Conference on Performance-based and Life-cycle Structural Engineering, 2015. School of Civil Engineering, The University of Queensland, 1433e1442.

[28] S. Shuid, Low Medium Cost Housing in Malaysia: Issues and Challenges, International Islamic University Malaysia, 2004.

[29] The Tenth Malaysia Plan, (2011–2015), Economic Planning Unit, Prime Minister's Department, Putrajaya, 2010.

[30] Buys, Aaron, Bendewald, Michael, & Tupper, Kendra, 2011. Life Cycle Cost Analysis: Is it Worth the Effort?.

[31] Z.A. Akasah, and N.A.M. Rum, Implementing Life Cycle Costing in Malaysia Construction Industry: a review. in: Proceeding of International Building and Infrastructure Conference, 7–8 June 2011.

[32] Building Materials Price (CIDB), 〈http://myn3c.cidb.gov.my/cidb_n3c/output/a_web_bmp_details.php?4〉.

[33] H.R. Lu, A. El Hanandeh, Life cycle assessment of ACQ-treated veneer based composite (VBC) hollow utility poles from hardwood plantation mid-thinning, Sustain. Prod. Consum. 5 (2016) (36e50).

[34] A.H. Buchanan, S. John, S. Love, LCA and carbon footprint of multi-storey timber buildings compared with steel and concrete buildings, World 15 (2012) 19.

[35] A.T. Balasbaneh, B.M. Kadir, New residential construction building and composite post & beam structure towards global warming mitigation, J. Environ. Prog. Sustain. Energy (2017), https://doi.org/10.1002/ep.12807 Wiley online library, 14 November.

[36] A.T. Balasbaneh, B.M. Kadir, Balancing of life cycle carbon and life cycle cost appraisal on alternative wall and roof design verification for residential building, J. Constr. Innov.: Inform, Process, Manag. (2018), https://doi.org/10.1108/CI-03-2017-0024.

[37] Shamim Ahmad, Ismail Sahid, Vijaya Subramaniam, Halimah Muhamad, and Anis Mokhtar, Life cycle inventory for palm based plywood: A gate-to-gate case study, Citation: AIP Conference Proceedings 1571, 569, 2013.

[38] The Malaysian electricity generation, Fossil fuel energy consumption, 2014a.

[39] Swiss Centre for Life Cycle InventorieS, 2016. The Life Cycle Inventory Data. Ecoinvent 3.3 ed.

[40] National Institute For Public Health and the Environment, 2016a. ReCiPe [Online]. Ministry of Health, Welfare and Sport, Netherlands. Available: 〈http://www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/ReCiPe〉. (Accessed 7 August 2017).

[41] D.E. Kline, Gate-to-gate life-cycle inventory of oriented strandboard production, Wood Fiber Sci. 37 (2007) (74e84).

[42] C.T.S. Nair and R. Rutt, Creating forestry jobs to boost the economy and build a green future, nineteenth session of the FAO Committee on Forestry, Rome, 20 March 2009.

[43] A.H. Buchanan, S. John, S. Love, LCA and carbon footprint of multi-storey timber buildings compared with steel and concrete buildings, World 15 (2012) 19.

[44] The Malaysian electricity generation, Fossil fuel energy consumption, 2014b. (Accessed on 17 April 2016). 〈http://www.tradingeconomics.com/malaysia/fossil-fuel-energy-consumption-percent-of-total-wb-data.html〉.

[45] R.C. Hyman, J.M. Reilly, M.H. Babiker, A. Masin, H.D. Jacoby, Modeling non-CO_2 greenhouse gas abatement, Environ. Model. Assess. 8 (2003) 175–186.

[46] M. Guo, X. Wang, J. Li, K. Yi, G. Zhong, H. Tani, Assessment of global carbon dioxide concentration using MODIS and GOSAT data, Sensors (Basel) 12 (2012) 16368–16389.

[47] A. Sharma, A. Saxena, M. Sethi, V. Shree, Varun, Life cycle assessment of buildings: a review, Renew. Sustain. Energy Rev. 15 (2011) 871–875.

[48] GDP Malaysia, 〈https://www.ceicdata.com/en/indicator/malaysia/data/gdp-construction〉.

[49] CEN (Comité Européen de Normalisation). Sustainability of construction works—Assessment of buildings—Part 3: Framework for the assessment of social performance., 2012. EN 15643-15643, Brussels, Belgium.

[51] United States Green Building Council (USGBC), The LEED reference Guide for GreenBuilding Design and Construction for the Design, Construction and Major Ren-ovations of Commercial and Institutional Building, 2009.

[52] International Energy Agency (IEA), World Energy Consumption by Sector, 2009 〈http://www.iea.org/stats/index.asp〉 (Accessed 26 January 2013).

[53] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (2008) 394–398.

[54] M. Dowden, Climate Change and Sustainable Development: Law, Policy andPractice, EG Books, 2008.

[56] Sweatfree Communities. Non-Poverty Wages for Countries Around the World. 2009 [cited 2016 April 24]; Available from: 〈http://www.sweatfree.org/nonpovertywages〉.

[57] Malaysia's average national poverty, [cited 24 April 2016]; Available from: 〈http://www.thepovertyline.net/malaysia/〉.

[58] World Bank. GDP per capita. World Bank; 2014 [cited 21 May 2016]; Available from: 〈http://data.worldbank.org/indicator/NY.GDP.PCAP.CD〉.

[60] Household income Survey (HIS) and Poverty Line Income (PLI) statistics, [cited 30 May 2017]; Available from: 〈http://www.epu.gov.my/en/socio-economic/household-income-poverty〉.

[62] Cathy Berry, Shaun McCarthy, Guide to sustainable procurement in construction, CIRIA C695 London, 2011, British Library Cataloguing in Publication Data.

[63] BMELV, 2013. in: Bundesministerium für Ern€ahrung, Landwirtschaft und Verbraucherschutz. BMELV (Ed.), Politikstrategie Bio€okonomie. Nachwachsende Ressourcen und biotechnologische Verfahren als Basis für Ern€ahrung, Industrie und Energie. Available online at: 〈http://www.bmbf.de/pubRD/Politikstrategie_Biooekonomie_barrierefrei.pdf〉. (Accessed on 1 December 2014).

[64] M. O'Brien, A. Doig, R. Clift, Social and environmental Life Cycle Assessment (SELCA) approach and methodological development, Int. J. Life Cycle Assess. 1 (1996) 231–237.

[65] S. Sala, F. Farioli, A. Zamagni, Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: part 1, Int. J. Life Cycle Assess. 18 (2013) 1653–1672.

[66] UNEP/SETAC, 2012. Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products. United Nations Environment Programme-Society of Environmental Toxicology and Chemistry Life Cycle Initiative.

[67] UNEP/SETAC, 2013. The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA). United Nations Environment Programme-Society of Environmental Toxicology and Chemistry Life Cycle Initiative.

[68] R. Foolmaun, T. Ramjeeawon, Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius, Int. J. Life Cycle Assess. 18 (2013) 155–171.

[69] S. Spillemaeckers, B. Mazijn, E. Borgo, An integrated approach to chain analysis for the purpose of chain management by companies. Study executed by the Centre for Sustainable Development. Gent, Belgium, 2001.

[70] C.A.S. Bork, D.J.D. Junior, J.O. Gomes, Social life cycle assessment of three companies of the furniture sector, Procedia CIRP 29 (2015) 150–155.

[71] National Institute For Public Health and the Environment, 2016. ReCiPe [Online]. Ministry of Health, Welfare and Sport, Netherlands. Available: 〈http://www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/ReCiPe〉. (Accessed 7 August 2017).

[72] CML - Department of Industrial Ecology, 2016. CML-IA Characterisation Factors [Online]. Netherlands University Leiden. Available: 〈https://www.universiteitleiden.nl/en/research/research-output/science/cml-iacharacterisation-factors〉. (Accessed 7 August 2017).

[73] A. El Hanandeh, Energy recovery alternatives for the sustainable management of olive oil industry waste in Australia: life cycle assessment, J. Clean. Prod. 91 (2015) (78e88).

[74] T. Grant, G. Peters, Best Practice Guide to Life Cycle Impact Assessment in Australia. Australian Life Cycle Assessment Society (Revision draft v3), Melbourne, 2008.

[76] R. Frischknecht, N. Jungbluth, H.J. Althaus, G. Doka, R. Dones, R. Hischier, S. Hellweg, S. Humbert, M. Margni, T. Nemecek, M. Spielmann, Mplementation of Life Cycle Impact Assessment Methods: Data v2.0, 2007. Ecoinvent report No. 3, Dübendorf, CH.

[77] MY-LCID. Malaysia Life Cycle Inventory Database. Available online: 〈http://MYLCID.sirim.my/my-lcid/〉 (accessed on 22 March 2016).

[78] D. Kellenberger, H.J. Althaus, N. Jungbluth, T. Künniger, M. Lehmann, P. Thalmann, Life Cycle Inventories of Building Products, 2007. Final report ecoinvent Data v2.0 No.7, Dübendorf, CH.
[79] U. Iyer-Raniga, J.P.C. Wong, Evaluation of whole life cycle assessment for heritage buildings in Australia, build, Environ 47 (2012) (138e149).
[80] T. Ekvall, B.P. Weidema, System boundaries and input data in consequential life cycle inventory analysis, Int. J. Life Cycle Assess. 9 (3) (2004) 161e171.
[81] Malaysia Inflation Rate, 2017, ⟨https://tradingeconomics.com/malaysia/inflation-cpi⟩.
[82] C. Deegan, Environmental costing in capital investment decisions: electricity distributors and the choice of power poles, Aust. Account. Rev. 18 (1) (2008) 2–15, https://doi.org/10.1111/j.1835-2561.2008.0002.x.
[83] A.K. Petersen, B. Solberg, Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden, Policy Econ. 7 (3) (2005) 249–259, https://doi.org/10.1016/S1389-9341(03)00063-7.
[84] Electricity Cost in malaysia, Power tariff hike for West M'sia in 2016 with rebate cut – Malaysiakini ⟨https://www.malaysiakini.com/news/322659⟩.
[85] R. Sathre Life-cycle energy and carbon implications of woodbased products and construction, 2007. ⟨http://diva-portal.org/smash/record.jsf?Pid=diva2%3A2032&dswid=8832⟩.
[86] S.A. Hosseinijou, S. Mansour, M.A. Shirazi, Social life cycle assessment for material selection: a case study of building materials, Int. J. Life Cycle Assess. 19 (2014) 620, https://doi.org/10.1007/s11367-013-0658-1.
[87] lDong-Xue Zhao, Bao-Jie He, Christine Johnson, Social problems of green buildings: from the humanistic needs to social acceptance, Renew. Sustain. Energy Rev. 51 (2015) 1594–1609.
[89] J.N. Rodrigues, A.M.P.G. Dias, P. Providencia, Timber-concrete composite bridges: state-of-the-art review, Bioresources 8 (2013) 6630–6649.
[90] M. Spielmann, R. Dones, C. Bauer, M. Tuchschmid, Life Cycle Inventories of Transport Services, 2007. Ecoinvent report N○ 14, v2.0, Dübendorf, CH.
[91] C.A. Bolin, S.T. Smith, Life cycle assessment of borate-treated lumber with comparison to galvanized steel framing, J. Clean. Prod. 19 (2011) 630e639.
[92] A.B. Robertson, F.C. Lam, R.J. Cole, A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: laminated timber or reinforced concrete, Buildings 2 (2012) 245e270.